

Flood Magnitude and Dynamics in the Ungauged Velabish River Basin, Albania, Based on Rainfall–Runoff Modeling

5 ABSTRACT

6 Reliable estimation of flood magnitudes is a fundamental requirement for the design of hydraulic
7 infrastructure, flood risk management, and the mitigation of flood-related impacts. In ungauged river basins, where
8 discharge observations are unavailable, this task becomes particularly challenging and is associated with considerable
9 uncertainty. This study presents a comprehensive assessment of flood hydrographs in the ungauged Velabish River
10 basin, which forms part of the Osumi river system in Albania. Flood simulation was performed using the semi-
11 distributed Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS). Six independent
12 meteorological scenarios were developed on the basis of precipitation data collected from stations located within and in
13 the vicinity of the basin. A frequency analysis of annual maximum daily precipitation was conducted, resulting in
14 depth–duration–frequency (DDF) relationships for each scenario. Design storm hyetographs were constructed using
15 regional rainfall characteristics and the alternating block method. Precipitation losses were estimated using the Curve
16 Number method, with spatially distributed curve numbers derived through Geographic Information System (GIS)
17 analysis under average antecedent moisture conditions. Surface runoff hydrographs were generated using the synthetic
18 unit hydrograph recommended by the Natural Resources Conservation Service, while baseflow was represented by an
19 exponential recession approach. Flood routing along the river network was simulated using the Muskingum–Cunge
20 method. The model produced complete flood hydrographs for return periods of 2, 10, 20, 50, and 100 years, including
21 peak discharges, flood volumes, and temporal flow distributions. Model results were evaluated through comparison
22 with peak flows estimated using the method of hydrological analogy, indicating acceptable agreement for low and
23 medium exceedance probabilities. The outcomes of this research provide valuable insights for flood risk assessment and
24 hydraulic design in ungauged basins and may support decision-making processes for engineers, researchers, and
25 policymakers in the region.

26 **Keywords:** Flood modeling; Ungauged basins; Precipitation frequency analysis; Curve Number method; Muskingum–
27 Cunge routing.

Introduction

30 Flood estimation plays a central role in hydraulic engineering, land-use planning, and disaster risk reduction.
31 Accurate knowledge of flood magnitudes and their temporal characteristics is required to design bridges, culverts, flood
32 protection works, and reservoirs, as well as to assess flood hazards and potential damages. However, in many regions,
33 especially in developing countries, hydrometric networks are sparse, and long-term discharge records are unavailable.
34 Under such conditions, river basins are classified as ungauged, and conventional flood frequency analysis based on
35 observed streamflow data cannot be directly applied.

37 In ungauged basins, rainfall data are often more readily available than discharge measurements. As a result,
38 hydrological modeling approaches that transform precipitation into runoff have become an essential tool for flood
39 estimation. Advances in computational capabilities and the development of physically based and conceptual
40 hydrological models have significantly improved the reliability of rainfall–runoff simulations. Semi-distributed models,
41 in particular, offer a balance between spatial representation and data requirements, making them suitable for catchments
42 where detailed observations are lacking.

43 The HEC-HMS model, developed by the U.S. Army Corps of Engineers, has been widely applied for flood
44 simulation, design storm analysis, and watershed management studies. Its flexible structure allows the integration of
45 various loss methods, runoff transformation techniques, baseflow representations, and routing approaches. In Albania,
46 several river basins remain ungauged, and systematic flood studies are limited. The Velabisht River, a tributary of the
47 Vjosa River, is one such basin where flood behavior has not been previously quantified in detail.

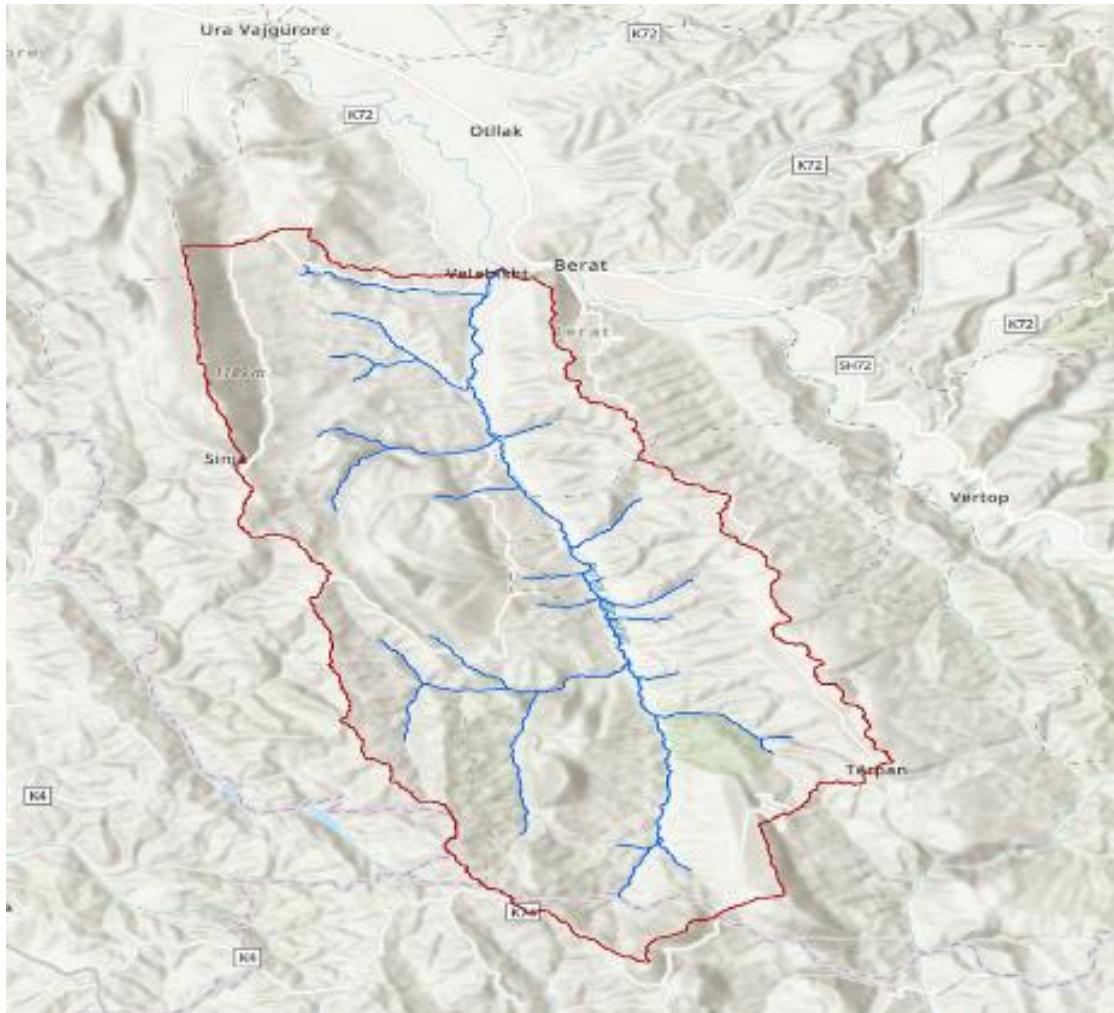
48 The primary objective of this study is to estimate flood hydrographs with different return periods for the ungauged
49 VelabishtRiver basin using the HEC-HMS semi-distributed model. Specific objectives include: (i) conducting
50 precipitation frequency analysis and deriving basin-average DDF curves; (ii) constructing design storm hyetographs for
51 selected exceedance probabilities; (iii) estimating precipitation losses and runoff generation parameters using GIS-based
52 analysis; (iv) simulating flood hydrographs and routing flood waves through the river network; and (v) validating peak
53 flow estimates through comparison with results obtained using the method of hydrological analogy. The results aim to
54 contribute to improved flood risk understanding and provide a scientific basis for hydraulic design and flood
55 management in the basin.

56 **Materials and methods**

57 **Setting up the Velabisht flood model**

58 The VelabishtRiver is one of the principal tributaries of the Osumi River, which in turn forms part of the
59 Osumi River system in southern Albania. The basin covers an area of approximately 183 km² and exhibits a
60 predominantly mountainous to pre-mountainous topography. The average elevation of the catchment is around 750 m
61 above sea level, with steep slopes in the upstream areas and gentler terrain downstream.

62 The regional climate is Mediterranean, characterized by cold and wet winters and dry, relatively mild
63 summers. Mean annual precipitation in the basin is approximately 1109 mm, while average annual evapotranspiration is
64 estimated at about 615 mm. The long-term mean discharge of the river has been estimated at 2.9 m³/s based on regional
65 hydrological studies, corresponding to a specific discharge of approximately 16 l/s/km² and an annual runoff coefficient
66 of 0.45. Despite its hydrological importance, the river is ungauged, and no continuous streamflow records are available.



The Velabist River basin map.

70 HEC-HMS model setup

71 Flood modeling was carried out using the HEC-HMS software. The model setup required the definition of
72 several interconnected components, including basin geometry, meteorological inputs, precipitation loss methods, runoff
73 transformation techniques, baseflow representation, channel routing, and simulation control specifications.

74 A digital elevation model (DEM) was used to delineate the basin, extract the drainage network, and subdivide
75 the catchment into hydrologically meaningful subbasins. Basin parameters such as area, slope, flow length, and stream
76 characteristics were derived directly from the DEM within a GIS environment and imported into HEC-HMS.

77 Six meteorological scenarios corresponding to different exceedance probabilities were defined. For each scenario,
78 precipitation inputs were specified as design storms derived from frequency analysis. The Curve Number method was
79 selected to estimate precipitation losses, while runoff transformation was performed using the NRCS synthetic unit
80 hydrograph. Baseflow was simulated using an exponential recession approach, and flood routing through the river
81 reaches was carried out using the Muskingum–Cunge method. Simulation periods were defined to exceed the duration
82 of rainfall events, ensuring full representation of flood hydrographs.

83

84

85 **Precipitation frequency analysis and meteorological scenarios**

86 Flood generation in the basin was based on precipitation frequency analysis using data from meteorological stations
87 located near the study area, with particular emphasis on the Sinj  station. Due to the characteristics of the available
88 records, precipitation data were available at daily time steps. Annual maximum daily precipitation series were extracted
89 and subjected to statistical frequency analysis.

90
91 Several probability distributions were tested to identify the most appropriate model for extreme precipitation.
92 Goodness-of-fit was evaluated using the Kolmogorov-Smirnov test, and the Generalized Extreme Value (GEV)
93 distribution was found to best represent the observed extremes. Based on the selected distribution, precipitation
94 quantiles corresponding to exceedance probabilities of 1%, 2%, 5%, 10%, 20%, and 50% were estimated. These
95 quantiles represent potential meteorological conditions capable of generating floods of varying magnitudes.

96
97 Since the basin concentration time is shorter than 24 hours, it was necessary to derive precipitation depths for
98 durations shorter than one day. Regional reduction relationships were applied to transform daily precipitation quantiles
99 into rainfall depths for durations ranging from 5 minutes to 12 hours. The transformation was performed using the
100 following empirical relationship:

$$h_{p,t} = H_{p,24} \left(\frac{t}{24} \right)^n \quad (1)$$

101 where $h_{p,t}$ is the precipitation depth for duration t (hours) and exceedance probability p (mm), $H_{p,24}$ is the 24-hour
102 precipitation depth with exceedance probability p (mm), and n is a station-specific reduction exponent derived from
103 regional analyses.

104 Basin-average precipitation values were estimated using the Thiessen polygon method, assuming a uniform spatial
105 distribution of rainfall across the basin. Since precipitation depths measured at a point exceed those averaged over an
106 area, areal reduction factors (ARF) were applied to account for spatial variability. For the basin area of 183 km², an
107 ARF of 0.93 was applied for the 24-hour storm duration. For shorter storm durations, appropriate ARFs were
108 automatically selected within the HEC-HMS modeling environment.

109 Depth-duration-frequency (DDF) curves derived from statistical analysis represent probabilistic rainfall estimates
110 rather than actual storm events. Therefore, frequency-consistent hypothetical storm events were constructed to serve as
111 model inputs. To generate realistic temporal rainfall distributions, the alternating block method recommended by Chow
112 et al. [7] was employed. Incremental rainfall depths were arranged such that the maximum intensity occurred at the
113 midpoint of the storm duration, producing temporally consistent design hyetographs for each exceedance probability.

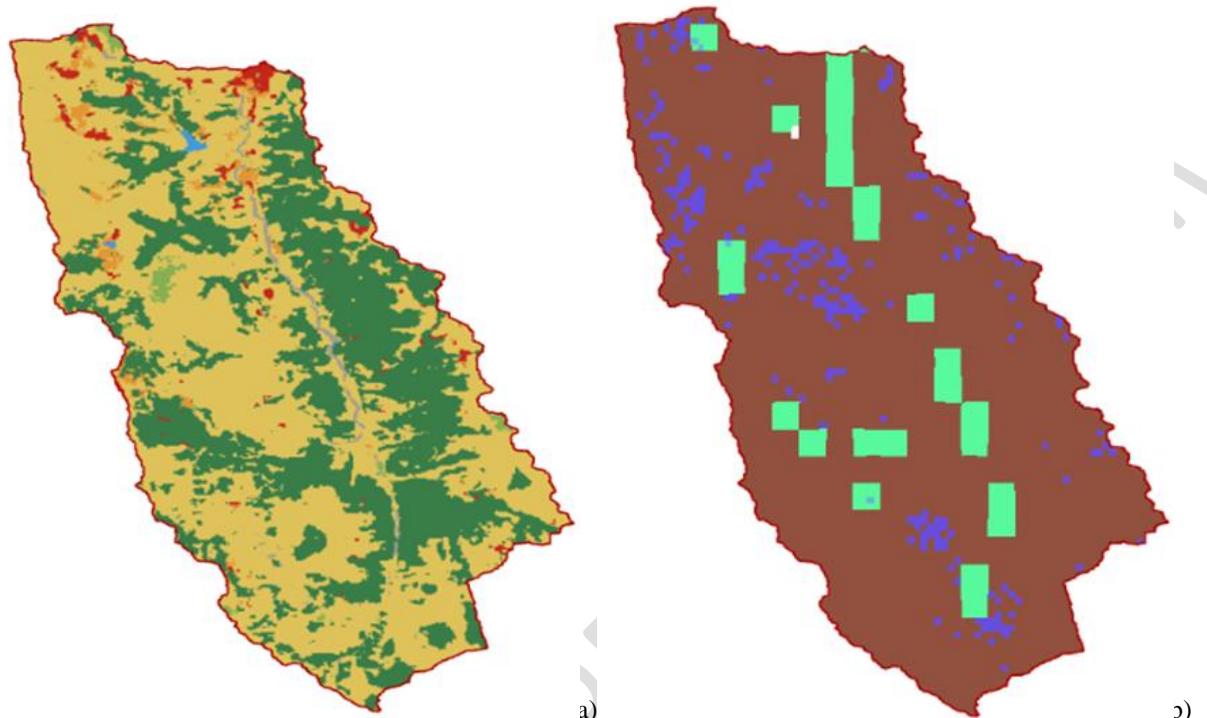
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115 **Net precipitation**

116 Effective rainfall was calculated using the Curve Number method developed by the Natural Resources
117 Conservation Service. This method relates direct runoff to total precipitation through a dimensionless parameter known
118 as the curve number (CN), which reflects the combined effects of land use, soil type, and antecedent moisture
119 conditions.

120 Land use information was obtained from high-resolution spatial datasets, while soil properties were derived from
121 the Harmonized World Soil Database. Hydrologic soil groups were identified and combined with land use classes to

122 assign CN values based on standard NRCS tables. Average antecedent moisture conditions were assumed, consistent
123 with typical design practice.

124 GIS analysis was used to overlay land use and soil maps and generate a spatially distributed CN grid for the entire
125 basin. Weighted CN values were then calculated for each subbasin and used as input parameters in the HEC-HMS
126 model to estimate precipitation losses



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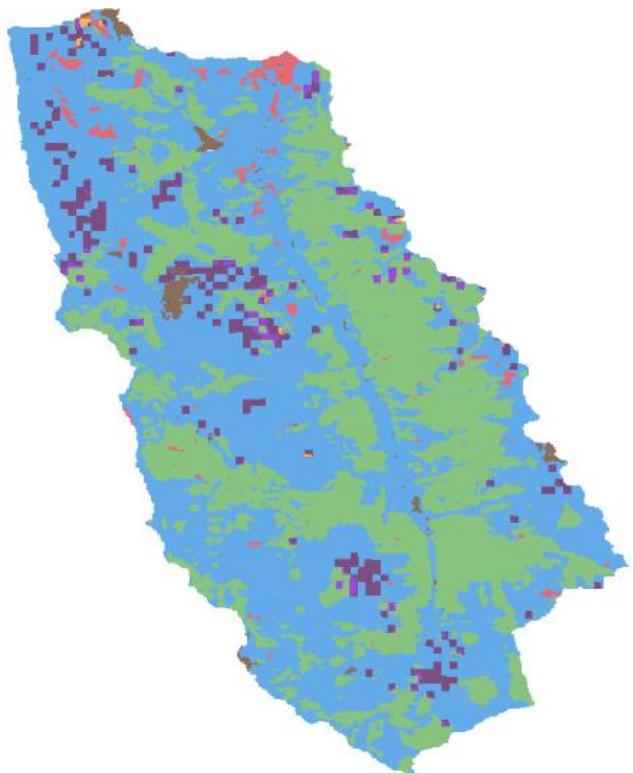
a)

b)

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Spatial distribution of Land Use (a) and Hydrological soil groups in Velabisht basin (b).

129



c)

130
131 **Spatial distribution of Curve Number values(c).**

132 **Hydrographs generation**

133 In the absence of observed rainfall

134 In runoff data, flood hydrographs were generated using the NRCS synthetic unit hydrograph (UH) method. This
135 approach is widely applied in ungauged basins and requires limited input data derived from measurable basin
136 characteristics. The Velabist River basin is ungauged and lacks historical rainfall-runoff observations; therefore, no
137 direct information regarding the shape or magnitude of flood hydrographs could be obtained from measurements.

138

139 Effective precipitation generated within each subbasin was transformed into direct runoff hydrographs using
140 the NRCS synthetic unit hydrograph. This method is suitable for ungauged basins and is applicable to drainage areas
141 well within the size of the Velabist basin (183 km^2) [10]. The unit hydrograph approach assumes linearity and time
142 invariance of the watershed response, allowing runoff hydrographs to be obtained through convolution of excess rainfall
143 with the unit hydrograph.

144 The NRCS unit hydrograph is a dimensionless function whose ordinates are defined based on the time-to-peak
145 and peak discharge. The time-to-peak depends on basin lag time and rainfall duration, while the peak discharge is
146 calculated as a function of basin area and time-to-peak [10]. Basin lag time represents the time elapsed between the
147 centroid of net precipitation and the peak of the resulting runoff hydrograph and reflects the physical runoff
148 characteristics of the basin.

149

150 Lag time for each subbasin was estimated using the NRCS empirical relationship:

$$t_l = \frac{L^{0.8}(2540 - 22.86 CN)^{0.7}}{14104 CN^{0.7}Y^{0.5}}$$

151 where t_l is the basin lag time (hr), L is the hydraulic length (m), CN is the runoff curve number, and Y is the average basin
 152 slope (m/m). Subbasin characteristics, including hydraulic length, curve number, and slope, were used to compute lag
 153 times, which were subsequently entered into the hydrologic model as transformation parameters for hydrograph
 154 generation.

155 **Baseflow**

156 Baseflow was incorporated into the simulations using the exponential recession method, which is commonly applied in
 157 event-based hydrologic modeling. This approach represents groundwater contributions to streamflow during and after
 158 storm events using a simple conceptual formulation. An initial discharge was specified at the beginning of each
 159 simulation and distributed among subbasins in proportion to their respective drainage areas.

160

161 According to this method, the recession limb of the hydrograph follows the exponential relationship:

$$Q_t = Q_0 k^t$$

162 where Q_t is the discharge at time t , Q_0 is the discharge at the start of the recession, and k is the exponential recession
 163 constant. Three parameters are required to simulate baseflow using this method: the initial discharge, the recession
 164 constant, and a threshold value that determines when the recession curve is initiated.

165 Historical records from the Velabisht River indicate an average annual discharge of 2.9 m³/s. Assuming that
 166 average flow conditions prevail in the river at the onset of flood events, an initial discharge of 2.9 m³/s was adopted and
 167 apportioned to each subbasin based on its contributing area. The recession constant was set to 0.55, following values
 168 recommended by Pilgrim and Cordery for basins with similar hydrological characteristics [2]. The baseflow initiation
 169 threshold was defined as a ratio of peak discharge and assigned a value of 0.001, reflecting the perennial nature of the
 170 river and ensuring a continuous baseflow contribution throughout the simulation period.

171 **Channel routing**

172 Flood routing along the river network was performed using the Muskingum–Cunge method, a physically based
 173 extension of the classical Muskingum routing approach. Unlike the original Muskingum method, Muskingum–Cunge
 174 incorporates channel geometry, slope, and roughness, allowing wave celerity and attenuation to vary with flow
 175 conditions. These features make the method particularly suitable for rivers with limited or no observed discharge data,
 176 such as the Velabisht River.

177 Routing parameters, including reach length, channel bed slope, Manning's roughness coefficient, and cross-sectional
 178 geometry, were estimated using GIS-derived data and available field information. Automatic selection of space–time
 179 intervals and the celerity index method were employed within the modeling framework to ensure numerical stability
 180 and realistic simulation of flood wave propagation.

181 The Muskingum–Cunge method simplifies the Saint-Venant equations by retaining the continuity equation and
 182 approximating the momentum equation using a diffusive-wave assumption, thereby neglecting inertial (acceleration)
 183 terms [11,12]. The governing equations can be expressed as:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = ql$$

$$S_f = S_o - \frac{\partial y}{\partial x}$$

184 where A is the cross-sectional flow area, Q is discharge, ql represents lateral inflow per unit channel length, S_f is the
 185 friction slope, S_o is the channel bed slope, and $\frac{\partial y}{\partial x}$ denotes the water surface slope along the channel. In these equations,
 186 $\frac{\partial A}{\partial t}$ represents the temporal change in flow area, while $\frac{\partial Q}{\partial x}$ represents the spatial variation of discharge along the channel.

187 **Comparison of flood peaks results**

188 Despite the absence of observed flood data in the Velabisht basin, an independent validation of the model
 189 simulation results was required. To this end, the method of analogy was employed, whereby peak discharges for various
 190 return periods were estimated for the Velabisht River based on data from a hydrologically similar, nearby gauged basin.

191 The hydrometric station of Ura Vajgurore, located on the Osumi River, was selected as the analogous basin
 192 due to its proximity and comparable hydrological characteristics. Flood quantiles observed at the Ura Vajgurore station
 193 were transferred to the Velabisht River using the following empirical area-scaling relationship:

$$Q_p = Q_a \left(\frac{A_a}{A} \right)^n$$

194 where Q_p is the flood quantile at the Velabisht River, Q_a is the corresponding flood quantile at the analogous station, A is
 195 the drainage area of the Velabisht basin, A_a is the drainage area of the analogous basin, and n is a regional reduction
 196 exponent, assumed equal to 0.5 based on literature recommendations [14].

197 Flood quantiles estimated for the Velabisht River using the analogy method were subsequently compared with
 198 the peak discharges obtained from the hydrologic model simulations. Relative percentage differences (RPD) were
 199 calculated for each return period to quantify the level of agreement between the two estimation approaches.

200

201 **1. RESULTS**

202 The precipitation frequency analysis demonstrated that the Generalized Extreme Value (GEV) distribution provides
 203 an adequate representation of annual maximum daily rainfall in the study area. Based on the selected distribution, basin-
 204 average depth-duration-frequency (DDF) curves were derived and subsequently transformed into design storm
 205 hyetographs. In total, six meteorological scenarios corresponding to exceedance probabilities of 1%, 2%, 5%, 10%,
 206 20%, and 50% were simulated.

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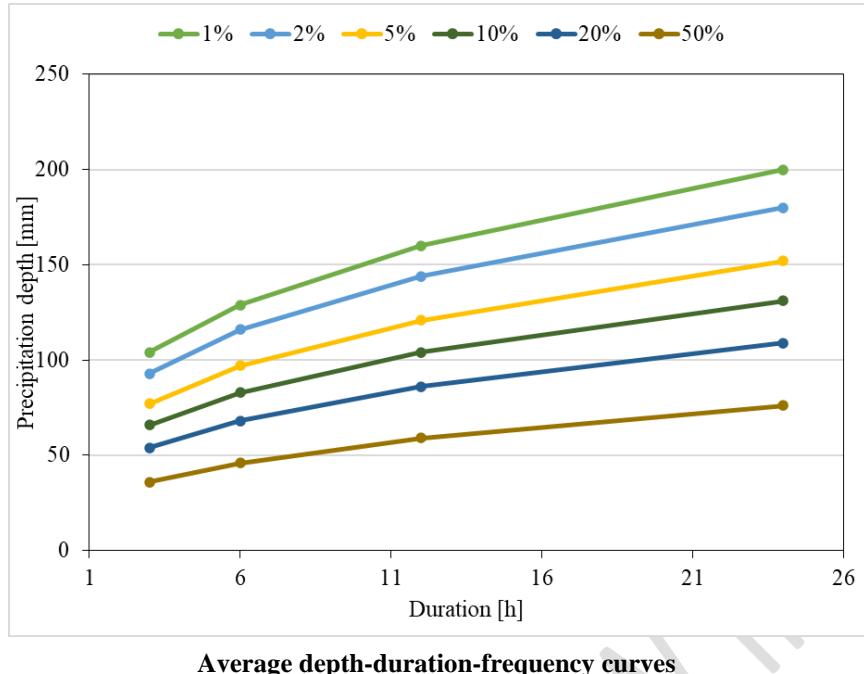
208 Hydrologic model simulations produced complete flood hydrographs for return periods of 2, 10, 20, 50, and 100
 209 years. For each scenario, key flood characteristics—including peak discharge, flood volume, and hydrograph shape—
 210 were obtained. As expected, peak discharges increased consistently with decreasing exceedance probability, reflecting
 211 the increasing intensity and severity of the design storm events.

212

213 To ensure full development and recession of the flood hydrographs, the simulation duration for all scenarios was set
 214 to 48 hours. The resulting flood hydrographs corresponding to exceedance probabilities of 1%, 2%, 5%, 10%, 20%, and

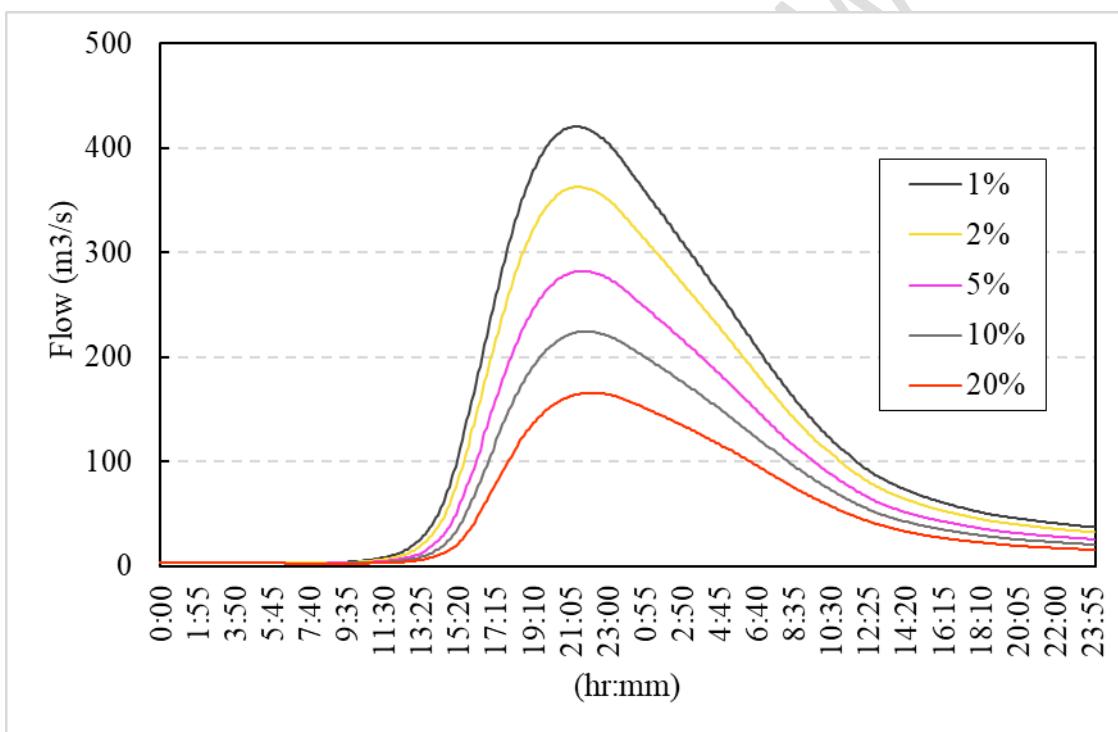
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50% were analyzed. Flood volumes and peak discharges for each return period are summarized in Table below.



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219

220 Flood hydrographs characteristics for different return periods

	Return periods (years)				
	100	50	20	10	5
Volume (Mm ³)	147.32	127.82	101.03	81.49	97.4
Peak discharge (m ³ /s)	420.4	362.7	282.2	224.3	166

221

222

223

To assess the plausibility of the simulated peak discharges, the results were compared with flood quantiles estimated using the hydrological analogy method, based on data from the Ura Vajgurore hydrometric station on the

224 Osumi River. Flood quantiles transferred to the Velabish River using basin-area scaling were compared with the
225 simulated peak flows, and relative percentage differences (RPD) were calculated for each return period.

226

	Return periods (years)				
	100	50	20	10	5
Simulated (m ³ /s)	420	363	282	224	166
By analogy (m ³ /s)	407	362	300	250	200
RPD (%)	13	1	-18	-26	-34

227

228 The comparison indicates good agreement between simulated and analogously estimated peak flows for high and
229 medium return periods, particularly for the 50- and 100-year events. Larger discrepancies observed for lower return
230 periods may be attributed to increased uncertainty in regional scaling relationships and model sensitivity under smaller
231 flood conditions. Overall, the results support the plausibility of the simulated flood hydrographs and confirm the
232 suitability of the adopted modeling framework for flood estimation in the ungauged Velabish basin.

233

234

Discussion

235 Flood hydrographs corresponding to different return periods were simulated under the assumption that the return
236 period of precipitation events is identical to the return period of the resulting flood events. Although this assumption
237 does not necessarily hold in reality—since antecedent moisture conditions, soil saturation, and basin storage vary
238 stochastically and may lead to flood events with return periods differing from those of precipitation—it is widely
239 adopted in design hydrology. This simplification allows for a consistent and systematic assessment of flood magnitudes
240 and provides decision-makers with a coherent framework for flood risk evaluation and infrastructure design.

241

242 All simulated flood hydrographs exhibit an identical shape, irrespective of their magnitude or exceedance
243 probability. This behavior is a direct consequence of the linear response assumption inherent in the unit hydrograph
244 theory, whereby runoff discharge is directly proportional to increments in effective rainfall. Consequently, the temporal
245 characteristics of the hydrographs remain unchanged across scenarios. The time to peak is constant for all return
246 periods, as the design storm hyetographs were constructed using the alternating block method with the maximum
247 rainfall intensity positioned at the midpoint of the storm duration. Furthermore, the recession limb of the hydrographs is
248 governed by a fixed recession constant, implying that baseflow decay does not significantly affect peak flow values,
249 even if subsequent flood events were to occur shortly after the simulated storms.

250

251 The comparison between peak discharges derived from the hydrological model simulations and those estimated
252 using the method of hydrological analogy indicates a generally good level of agreement. For return periods ranging
253 from 20 to 100 years, absolute percentage differences between the two approaches vary between approximately 3.1%
254 and 6.3%, suggesting that the simulated flood peaks are plausible within the context of the inherent uncertainties
255 associated with both hydrological modeling and regional transfer methods.

256

257 For lower return periods (5–10 years), the absolute percentage differences are notably higher, ranging from
258 approximately 11% to 21%. These discrepancies are most likely influenced by the shape of the flood frequency curve
259 derived for the Ura Vajgurore hydrometric station. Flood frequency curves for Albanian rivers are commonly
260 characterized by positive skewness. A positively skewed distribution tends to overestimate flood quantiles associated
261 with higher exceedance probabilities, while the lower tail of the distribution is associated with increased uncertainty and
262 wider confidence intervals. Consequently, flood estimates corresponding to frequent events are less reliable when
263 transferred using analogy-based methods, particularly when they rely on the extrapolation of the less well-fitted portion
264 of the frequency curve at the gauged site.

265

266 Based on these considerations, it can be inferred that the simulated flood peaks for higher return periods are more
267 physically consistent and reliable than those estimated using the analogy method for frequent events. Overall, the
268 modeling results demonstrate reasonable agreement with the analogy-based estimates, particularly for low and medium
269 exceedance probabilities, thereby supporting the robustness of the adopted hydrological modeling framework.

270

271 Nevertheless, uncertainties remain in the simulation results due to assumptions related to model parameters,
272 particularly those associated with flood routing and loss estimation. Muskingum–Cunge routing parameters are ideally
273 calibrated using observed inflow–outflow hydrographs; however, such data were unavailable due to the ungauged
274 nature of the Velabisht basin. Even in gauged basins, routing parameters are known to vary between events, introducing
275 additional uncertainty. Similarly, the use of design storm hyetographs further complicates parameter evaluation, as
276 routing parameters cannot be dynamically adjusted based on observed flow responses.

277

278 Curve Number (CN) values, although generally associated with lower uncertainty compared to routing parameters, also
279 contribute to overall model uncertainty. These values were selected from standard NRCS tables, which were originally
280 developed based on small experimental watersheds and may not fully represent local hydrological conditions.

281

282 To reduce these uncertainties and improve the reliability of future flood assessments, the establishment of systematic
283 hydrometric and pluviometric monitoring in the Velabisht River basin is essential. Continuous discharge measurements
284 would enable calibration and validation of model parameters, leading to more accurate flood predictions and improved
285 flood risk management.

286

Conclusion

287 In this study, the semi-distributed HEC-HMS hydrological model was applied to simulate flood hydrographs
288 corresponding to exceedance probabilities of 1%, 2%, 5%, 10%, 20%, and 50% in the Velabisht River basin, Albania.
289 Basin-average depth–duration–frequency (DDF) curves were derived from annual maximum daily precipitation records
290 and subsequently used to construct design storm hyetographs that served as model inputs. Loss parameters and basin lag
291 times were estimated for each subbasin to compute effective precipitation and generate synthetic unit hydrographs.

292 Flood wave propagation through the river network was simulated using the Muskingum–Cunge routing
293 method, with routing parameters determined for each river reach based on channel geometry and slope characteristics.
294 Baseflow contributions were incorporated using literature-based parameter values. The hydrological model produced

295 complete flood hydrographs for return periods of 2, 10, 20, 50, and 100 years, thereby providing a comprehensive
296 representation of flood magnitudes within the Velabisht River basin.

297 The results demonstrate that variations in assumed model parameters can influence the temporal distribution of
298 flood hydrographs and, consequently, peak discharge estimates. Simulated peak flows were compared with flood
299 quantiles derived using the hydrological analogy method, showing good agreement for low and medium exceedance
300 probabilities. Given the ungauged nature of the basin, the simulated flood hydrographs cannot be regarded as exact
301 representations; however, they provide a reasonable and physically consistent approximation of flood behavior in the
302 Velabisht River basin.

303 The findings underscore the importance of establishing systematic hydrometric monitoring within the basin to
304 reduce uncertainty and improve model calibration and validation. Nevertheless, the results offer valuable insights into
305 flood characteristics and can support policymakers in developing flood risk management strategies and informed
306 decision-making. Furthermore, the outcomes of this study are relevant for engineers and researchers involved in flood
307 analysis and water resources management in the Velabisht River basin and the broader Osumi River catchment.

308

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